

FROZEN-WAVE HERTZIAN GENERATORS:  
THEORY AND APPLICATIONS

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Abstract

"Frozen Wave" Hertzian generators have been built which can produce multikilowatt RF pulses in the megahertz frequency range with repetition rates of 10's of kilohertz. These generators do not have a damped sinusoidal output; they generate a discrete, controllable number of rectangular half cycles. The output waveform can be discretely changed from one half-cycle to the next. At the higher frequencies, discontinuities in the switch and dispersion in the cables round the edges of the rectangular half cycles, causing the output waveform to be nearly sinusoidal. These generators have also been used as video pulsers with variable pulse duration and interpulse spacing. Frequency, power and pulse width limitations will be discussed.

Introduction

In recent years there has been an increased interest in Hertzian generators as a means of generating extreme RF power levels. Most of these devices (e.g. L-C oscillators) produce an RF envelope whose amplitude function is a decaying sinusoid, limited in time by internal damping as well as dissipation in an external load. They cannot generate a short RF pulse with a rectangular envelope as is frequently desired in very short-range radars and some communication requirements.

This paper describes the design and implementation of a distributed parameter "frozen wave generator" (FWG) which can be used as an RF source and as a video pulser with variable pulse duration and interpulse spacing. The first part of the paper will

consider FWG's as high repetition rate, short pulse length RF generators; the last part will describe FWG's as video pulse generators with variable pulse duration and interpulse spacing. All of the generators considered here are constructed from standard 50 ohm coaxial cable. However, any transmission line (e.g. stripline) which can be adequately matched to the switch and load could be used.

FWG As An RF Source

To understand how the FWG operates consider an early multiple-switch version of the generator (Fig. 1a). In this device, energy from a power supply is statically stored in alternately charged sections of the transmission line. When the FWG is used as an RF source, there are an even number of cable sections, all  $\lambda/2$  in length (for the operational frequency of the device). A two cycle device is illustrated here. If the static potential on the outer conductors is plotted as a function of distance (d) along the cable, one obtains the static spatial potential distribution shown in Figure 1b. A two-cycle square wave pulse is "frozen" in the cable. The charging resistors  $R_c$  serve to isolate the power supply from the FWG, thereby protecting the power supply when the switches close. If the switches are assumed to be perfect and are closed simultaneously, a series of traveling waves is initiated in the cable sections which allows the previously frozen wave train to move through and dissipate in the load. Two traveling waves traveling in opposite directions are initiated at each switch. However, the effect of all of these waves is that two replicas of the initial frozen wave move in opposite directions toward the load.

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If the load is matched to the generator ( $R_L = 2 Z_0$ ),  $R_L$  effectively terminates the transmission lines and no reflections occur. Since the cables discharge into a matched impedance the potential at each side of the generator is one-half the charging potential of each cable. In this case the voltage-time waveform generated across the load is exactly analogous to the spatial waveform shown in Figure 1b. The potential on one side of the load becomes  $(+V_0/4)$  while the other side becomes  $(-V_0/4)$ ; hence, the potential difference across the load is  $V_0/2$ . After half a period the potentials at each end of the load reverse, again developing a potential difference of  $V_0/2$  but now with the opposite polarity. The time for each half cycle (half period) is  $\lambda/2v_p$ , where  $\lambda/2$  is the length of the cable section and  $v_p$  is the propagation velocity in the cable.

If  $R_L$  does not terminate the generator transmission lines, reflections will occur at the load. These reflections will complicate the waveform across the load especially in late time. Under certain special conditions part of the load can be mismatched to obtain longer waveforms. This case will be treated in the latter half of this paper.

The multiplicity of switches needed to operate a generator in this configuration necessitates precision triggering with a switch jitter that is much less than a period of the frequencies of interest. This restriction would keep the FWG a laboratory curiosity if it were not possible to replace the multiplicity of switches with a single switch. In Figure 1a note that the ends of each cable section are at the same potential. This permits one to fold the cable sections into half loops about a single switch as shown schematically in Figure 2. The center conductor is still continuous throughout the cable sections with the load across its ends. In this configuration the static or frozen wave is stored in the cable sections just as in Figure 1a. When the switch is closed, replicas of the frozen wave again effectively travel in both directions to the load.

As shown in Figure 2, the FWG is a continuous length of the cable with a discontinuity in the

outer conductor every half wavelength (i.e. the switch does not maintain the 50- $\Omega$  geometry). As more  $\lambda/2$  cable sections are added to the generator, the later cycles in the RF pulse must travel through the switch more times, causing the waveform to degrade progressively.

Attempts have been made to solve this problem by minimizing the discontinuity associated with the spark gap switch. At the present time, only about 1 cm of unshielded cable length is necessary to insert the switch.

Ideally, the addition of more cable sections to the FWG circuit should correspondingly produce more RF cycles. However, because of the discontinuity of the cable impedance at the switch, it is difficult to generate more than two or three cycles with an acceptable waveform at the hundreds-of-megahertz frequencies. Four to eight cycles are practical at tens-of-megahertz frequencies.

The repetition rate of these generators is limited chiefly by the spark-gap switch's turn-off time; the switch must open before recharging for the next pulse can begin. Dielectric gas species have been important factors in the development of the spark gap switches. A number of empirical experiments have led to a gas mixture which is 95-percent argon and 5-percent hydrogen. This mixture exhibits the fast spark-quenching characteristics of argon which are necessary for high PRF and the high-voltage standoff capability which is characteristic of hydrogen. Another advantage of this mixture is that it generates very few decomposition products in the gap.

Table 1 shows the general performance characteristics of some of the FWG's built at NAVSWC. The numbers represent levels at which the devices can perform at 10- to 20-min. intervals. Higher performance may be obtained for shorter times.

Table 1.

Device	Peak Power (kW)
2 cycle ( $\sim 130$ MHz)	60
Dual 2 cycle ( $\sim 130$ MHz)	10
2 cycle (40 MHz)	1400
3 cycle (60 MHz)	1500
2 cycle ( $\sim 800$ MHz)	20

Characteristics of FWG built by NAVSWC/DL.

### FWG As A Variable Pulse Width Video Pulse Generator

A cursory examination of the FWG schematically illustrated in Figures 1 and 2 may lead one to believe that waveforms with consecutive half cycles of different periods could be generated by merely using appropriate cable sections of unequal length. However, a closer examination indicates that this is impossible unless the frozen waveform is anti-symmetric about its center. Since the frozen wave effectively travels in both directions toward the load, any asymmetry would cause the voltage across the load to be different than that of the frozen wave since the potentials at the ends of the load would no longer invert their respective potentials at the same time (since the half periods are not equal).

To elucidate this problem further, consider a FWG with two cables of unequal lengths  $\ell_1$  and  $\ell_2$ . The static potential distribution or frozen wave of this arrangement is illustrated in Figure 3a. The temporal potential on one side of the load would be given by the waveform in Figure 3a. (Again the potential is halved because the cables are discharging into a matched load. The values for the temporal waveform are given in parenthesis.) The potential on the other side however would be the time inverse of Figure 3a given in Figure 3b. The potential across the load would therefore be the difference between the Figure 3a and 3b waveforms, i.e. Figure 3c. For the time corresponding to the half period of the short cable the output waveform is what would be expected; however, after this time gross distortions in the output wave compared to the frozen wave occur. A half period corresponding to the longer cable never occurs.

To overcome this problem the configuration of the FWG must be changed to permit an unbalanced output. Figure 4a illustrates one way to accomplish this. For simplicity a two cable generator is considered. The cables are again of unequal lengths  $\ell_1$  and  $\ell_2$ . The output of the FWG has been divided into  $R_L$  and  $R_T$ . Usually  $R_L$  is the load and  $R_T$  a terminating resistor. If  $R_L$  and  $R_T$  both equal the surge impedance ( $Z_0$ ) of the transmission lines no reflections will occur at the load. However, the wave

statically frozen in the generator is much different than in the previous configuration. Cable  $\ell_2$  in Figure 4a has no potential difference between its inner and outer conductors, while cable  $\ell_1$  has the entire potential  $V_0$  across its inner and outer conductors. If one starts at  $R_L$  and travels clockwise around the FWG cables, the static spatial potential distribution is given by Figure 4b.

The output waveform across  $R_L$ , a video pulse ( $V_0/2$ ) high and  $(\ell_1/v_p)$  long, is illustrated in Figure 4c. This corresponds to only half of the energy stored in the FWG; the outer half is dissipated in  $R_T$ . The waveform in  $R_T$  is shown in Figure 4d. From the Figures 4c and 4d one observes that cable  $\ell_2$  acts merely as a delay cable for the pulse which is stored in cable  $\ell_1$ .

Consider now the case in which  $R_T \gg Z_0$  such that the FWG can still charge properly, but where  $R_T$  looks like an open circuit to a pulse traveling in cable  $\ell_2$ . Then the pulse generated in  $\ell_1$  and traveling through  $\ell_2$  will be reflected in phase at  $R_T$ . This reflected wave will then travel through  $\ell_2$  and  $\ell_1$  and be absorbed in  $R_L$ . The output waveform in  $R_L$  will then be as shown in Figure 5a. The number of pulses have doubled and theoretically all of the energy stored in the FWG is dissipated in  $R_L$ .

Consider next the case in which  $R_T \ll Z_0$ ;  $R_T$  then looks like a short circuit to a pulse traveling in cable  $\ell_2$ . The pulse traveling in  $\ell_2$  will then be inverted and reflected at  $R_T$ . The output waveform will be as shown in Figure 5b. Once again the number of pulses have doubled and theoretically all of the energy stored in the FWG is dissipated in  $R_L$ . By using different cable lengths for cables  $\ell_1$  and  $\ell_2$  pulses of various pulse widths and pulse spacing can be obtained. By adding more cables more pulses can be obtained. The only constraint is that the later pulses must travel through the switch discontinuity more times, and they are thereby degraded.

To verify that these waveforms could be obtained, several low power ( $V_0 = 9$  volts) FWG's were constructed. A mercury wetted reed switch was used to switch these FWG's instead of spark gap switches. A generator which has the same basic configuration

as Figure 4a will now be described in more detail.

A six segment (3 cables charged and 3 delay lines) FWG was constructed. Starting at the load end ( $R_L$ ) of the generator the cable section half periods were, respectively: 50ns, 40ns, 30ns, 20ns, 10ns, and 5ns.  $R_T$  was chosen such that  $R_T \gg Z_0$ . Figure 6a is the output current waveform in  $R_L$ . As expected there is a 50-ns pulse followed respectively by a 40-ns delay, a 30-ns pulse, a 20-ns delay, a 20-ns pulse, and a 5-ns delay. The pulse then reflected by  $R_T$  follows in inverse time with the same polarity: 5-ns delay; 10-ns pulse, 20-ns delay, 30-ns pulse, 40-ns delay and 50-ns pulse. For this waveform one can also observe that the shorter pulse lengths (higher frequencies) and later pulses suffer the most degradation.

Additionally, if the terminating resistor  $R_T$  is made equal to  $Z_0$ , it will have the current waveform shown in Figure 6b. Since the 5-ns uncharged cable section is nearest  $R_T$ , the waveform will be: a 5-ns delay, 10-ns pulse, 20-ns delay, 30-ns pulse, 40-ns delay, and 50-ns pulse. This is the end of the waveform since  $R_L$  terminates the other side of the FWG; hence, there is no reflected pulse.

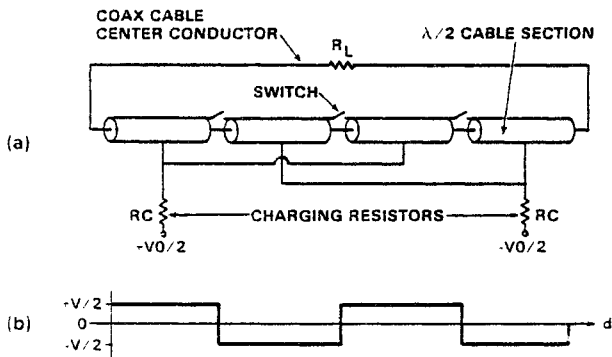


Fig. 1. Multiple Switch Frozen Wave Generator  
a) Schematically  
b) Static Spatial Potential Distribution in the Generator

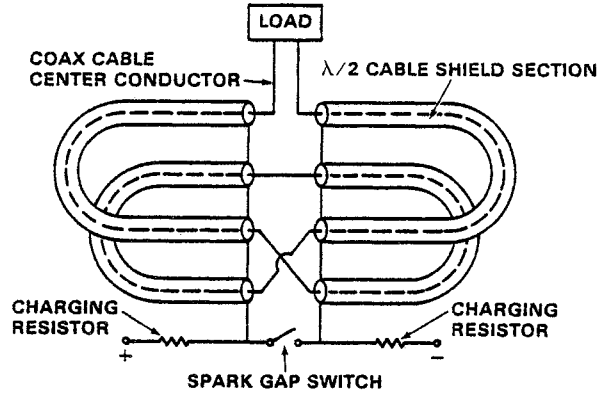


Fig. 2. Single Switch, Two Cycle FWG.

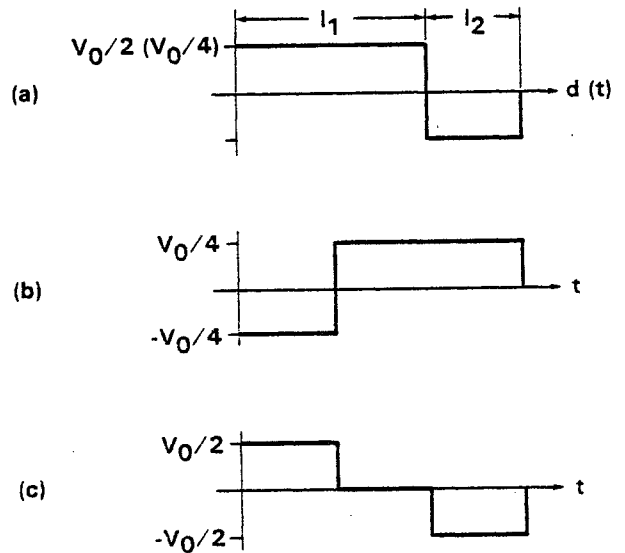


Fig. 3. (a) Static Spatial Potential Distribution for Unequal Length cables (temporal potential waveform on one side of the load is given in parenthesis)  
(b) Time Inverse of 3a (this is the temporal potential distribution for the other side of the load)  
(c) The Potential Difference across the Load (3b subtracted from 3a).

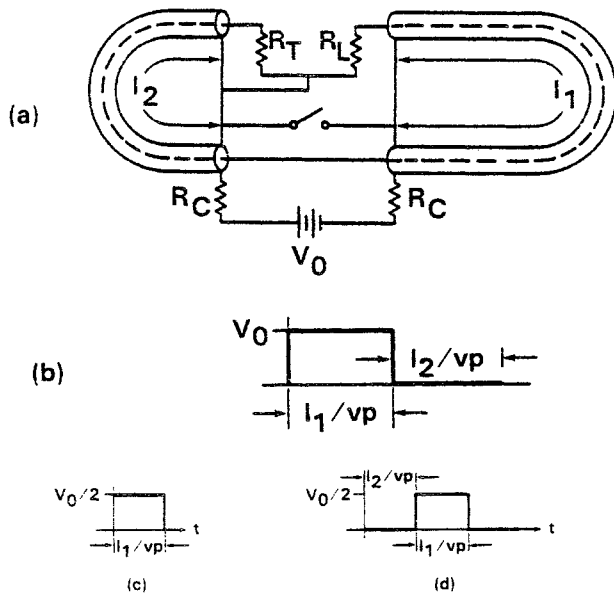


Fig. 4. Video Pulse

- (a) Schematically
- (b) Static Spatial Potential Distribution
- (c) Temporal Voltage Waveform across  $R_L$
- (d) Temporal Voltage Waveform across  $R_T$

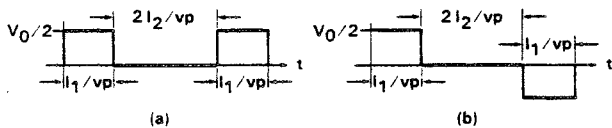


Fig. 5. (a) Voltage Waveform across  $R_L$  for  $R_T \gg Z_0$

(b) Voltage Waveform across  $R_L$  for  $R_T \ll Z_0$

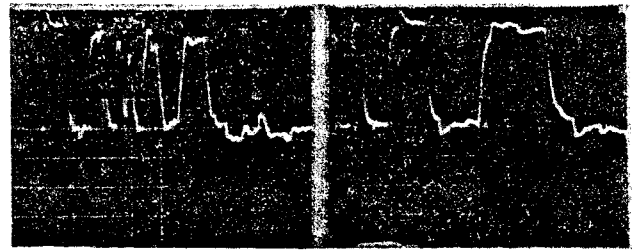


Fig. 6. Current Waveforms for a Six Element Video Pulse FWG

- (a) Current Waveform in  $R_L$  for  $R_T \gg Z_0$  (50 nS/div)
- (b) Current Waveform in  $R_T$  for  $R_L = Z_0$  (20 nS/div)

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